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ON THE ORIGIN OF FIORDS.*

BY

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SECTION III.—Our present knowledge of fiords did not come all at once, but is the result of a steady accumulation of material relating to their features. Obviously, then, theories for the explanation of the origin of fiords show a development as well. The earlier explanations were based on the facts then known, and when further investigation revealed facts and relations formerly unknown the old theory became inadequate and a new one superseded it.

In the early study of fiord-form the fact of the great depth of the channel beneath the surface of the sea, coupled with the idea that rivers cannot cut channels much below sea-level, led to the supposition that the fiord channel was once a river valley of the land which had been submerged, allowing the sea to flow in for miles and drown it. Then, a more careful study of the channel floor, both beneath the fiord and up the channel, where the bottom is exposed, led to grave doubts as to the power of the river to cut a channel with such a floor. With this more detailed study came a theory supposing the fiord channel to be a "graben" or depression due to faulting and the dropping down of a block of rock. If faults are the cause of fiords they must be recent, because the fiords are in channels made since the last great uplift; channels which have been cut down below the erosion surface then uplifted, and now represented by the uplands. The fiords are so recent that their bare walls are scarcely weathered at all, and possess very little vegetation. Usually they are covered with scratches and grooves and have square shoulders, neither of which has yet been destroyed by disintegration. Faults in Norway are known to be ancient—much older than the last great uplift and the previous cycle of erosion which made the present upland surface. Again, if faults be the cause, they must accord with the drainage systems, because the fiords almost universally do. It is scarcely supposable that a system of faults whose origin is deep-seated should correspond with the watercourses of the surface topography. In Norway the faults do not agree with the drainage systems. These two objections to the theory of fiords by faults are just as strong in Scotland and Labrador as in Norway. Moreover, fiords are wanting in many other regions where faults occur abundantly; and fiords sometimes occur where faults are unknown. True, great faults occur in one arm of the Christiania fiord, Norway; but this arm is not so fiord-like as the other, where both walls are alike of hard gneiss.

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* Continued from page 337.

† This paper was prepared as a thesis in geography under Prof. W. M. Davis, at Harvard University.

Fiords have been thought to be specially dependent upon strong relief, upon high latitude and great snowfall. To these suggestions it has been answered that fiords do not occur in all regions having these characteristics; nor do all fiord regions possess these features. All fiords occur in regions recently glaciated, which may suggest a relation between glaciation and fiords. Direction of mountain ridges, with reference to coast-line, folding of strata, and rock texture and composition, has also been thought to furnish necessary conditions for the production of fiords. A reference to the following facts will show the weight to be attached to these elements. The rocks of the Norway fiord region are mostly Archean gneisses; of Sweden, Silurian strata overlying similar gneisses; of northwest Scotland, Archean schists. The western coast of Greenland is known to be Archean gneiss; while Disco Island is Cretaceous. Labrador and the southern part of Baffin's Land are Archean, but the northern part of the latter is Carboniferous. On the Pacific coast of North America the fiords occur in Mesozoic and Tertiary rocks. Penck* thus sums up his discussion: "Fiords occur in faulted rocks in Norway, Scotland, and Greenland, and in folded rocks in Patagonia, British Columbia, and New Zealand." Some occur in crystallines, some in sedimentaries; some where mountains are parallel to the coast, and some where they are transverse to it.

Another theory which has existed a good many years, and which has recently been gaining much more general acceptance, is that of glacial erosion by ice streams. Fiords were first ascribed to ice work in 1827 by Esmark; but the theory was considered absurd at that time, because the work was deemed too great for the agent. Later studies have led to the conclusion that ice-covered Greenland explains Norway; while exposed Norway explains Greenland. It has been pointed out by more than one observer that fiords are confined to regions recently glaciated. They are features of coasts in high latitudes, and are best developed in coasts of strong relief which have been at some time subjected to glacial conditions.

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* Morph. der Erdoberfläche, 1894, II, 564.

A hasty glance at a little calculation, based on observations in regions of flowing stream ice, will help to elucidate the problem, and some comparative study will show the application of the glacial theory to it. In Muir Inlet, Alaska, the ice front of Muir glacier rises in a palisade two hundred feet above the water, and a short distance in front of the ice the water has a depth of seven hundred and twenty feet. If we calculate that a block of glacier ice floats in sea-water with one-sixth* of its volume above water, the two hundred feet of ice in view is more than enough to hold the seven hundred and twenty feet below water. On the supposition that the water does not shallow from the sounding to the ice front, the total thickness of the ice will be nine hundred and twenty feet, and the ice will rest on the bottom with a weight equal to a sheet of ice fifty-six feet thick, or about twenty-eight hundred pounds per square foot. If the water has shallowed towards the ice front the load on the bottom of the channel is greater. Russell† finds evidence that the ice has been much thicker here, and has extended farther seaward. He finds erratics on the flanks of bordering mountains two thousand feet above the present ice surface. The entire weight of this added thickness would be added to the calculated weight, and, with sea-level constant, would give a total pressure of over one hundred thousand pounds per square foot. Arm this ice with pebbles and boulders on its under surface and you have a rather formidable agent of erosion. After this glacier had cut a channel twenty-two hundred feet below the present sea-level it would still rest on the bottom with a weight of fourteen thousand pounds per square foot, and if still in motion would have considerable cutting power. If the land were somewhat depressed, that would prevent a part of the cutting calculated above, for it would allow the water to float up the ice; but if the land were at a higher stand the pressure would be greater and the power to erode would be increased. Probably at a sufficiently great pressure the ice in the lower layers would be softened or melted by pressure, and thus be unable to hold its tools.‡ Two questions arise—(*a*) At what pressure would it melt?

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* This proportion is taken because much glacier ice is not compact, and because sea-water, into which it extends, is saline—hence of greater density than fresh water. If it be thought that the true proportion should be 1:8 or 1:9, on account of greater assumed density for ice, or because of detrital material in the ice, that will make the first figures still more convincing.

† Glaciers of North America, 1897, 90.

‡ Experiments have demonstrated that a pressure of one atmosphere will lower the melting-point of ice 0.0135° F. Then 75 atmospheres, or about 158,000 pounds per square foot, would lower it one degree. This pressure, on the basis of the data used above, is equivalent to a thickness of 3,000 feet of ice.

This depends on its temperature, which is believed to be only a few degrees below the ordinary freezing-point. (*b*) If a change due to pressure occurs, would the ice become so fluid as to be unable to hold its tools, or would it simply become more plastic? If the temperature of the lower layers of ice be more than one or two degrees below the normal freezing-point, the second question need not concern us, because no such thickness of ice is required for the postulated ice erosion as would be necessary to fuse by pressure those layers at the bottom.

There are two processes to account for the uneven floor of the channels, both of which have probably played their part.

1. If the ice-tongue ran out to sea, nearly to the edge of the continental shelf, there would be formed a channel beneath the sea leading out as far as the ice-tongue had power to cut. This prolonged submarine channel is sometimes found. If the supply and waste maintained such a relation that the glacier could get no farther than the inner mouth of the fiord, obviously the channel would cease at that point. Since the glacier usually wastes and becomes smaller, the farther it flows from the supply, the end would be unable to cut as deeply as the portion a short distance inland, and would form a gently rising swell at the entrance to the channel. This, as pointed out in the description of Section I, is just what is found in the mouths of most fiords. A rapid recession, followed by a long stand at another point farther inland, would leave another sill deeper in the channel, with a basin between it and the former sill. Should the retreat and prolonged stand alternate, a series of swells and basins might be left all along the channel.

2. Again, if the ice encountered variations in the resisting power of the rock floor and walls, it would cut a depression in the weaker places, and leave transverse swells or sills in the stronger ones. On its final retreat, inequalities would remain the entire length of the channel, as so often observed in the landward portion beyond the head of the fiord. When a depression is started, the ice becomes thicker over it, because the upper surface of an ice stream tends to become rather uniformly graded. With increased thickness comes increased weight and decreased velocity. These changes may proceed until the ice ceases to move and erode in its lower layers. The scratches up the slopes of many deep basins, now exposed, indicate that the ice can pass, and has passed, out of them.

When a tributary glacier comes into the master ice stream the load on the bottom of the main channel is increased; consequently, at the confluence of two fiord channels a deeper basin may be expected. Several such have been noticed by explorers. In a general way the broad part of a channel is shallower than the narrow part. For a similar reason the shallow side at a bend in the channel is on the inside.

According to Playfair's law, tributary streams of water enter the master stream by nicely-adjusted valleys, none of them too high or too low. Observation confirms the statement so far as the surface of the water in mature valleys is concerned, for at the mouth of the side stream the water surface of each is at the same level. But if the water be withdrawn from the channels it is equally evident that the bed of the smaller channel is somewhat above that of the larger one. This is necessarily so, because the little stream can only cut the channel deep enough to bring its own surface to the level maintained by the water of the master. Confluent streams, then, while having their surfaces and valley floors adjusted to the same level, will have discordant channel floors or beds. The amount of discordance will be an expression of the ratio of the volumes of the master and tributary streams, and a function of their respective drainage areas and run-off.

A glacier system in a mature state has its side streams entering the master stream, with their upper surfaces at accordant levels. If the master stream is a thousand feet thick, and the tributary has a thickness of two hundred feet, it is evident that the side stream cannot cut its channel deeper than two hundred feet below the common level of the uniting streams, while the master will have cut one thousand feet below the same level. It then appears that the floor of the side channel will be eight hundred feet above that of the trunk channel. A nice problem for study, and one pertinent to the subject of fiord origin, is to determine whether this discordance bears a definite relation to the drainage areas and to the precipitation on them, as seems to be the case with rivers. While the streams of ice, like water streams, seem, when flowing, to unite in nicely-adjusted channels, they are discovered to have been in discordant channels if the ice and water be removed. The discordance of channels, together with the usual evidence of glaciation —bare, scratched rock surfaces and erratics—is a very good demonstration that stream ice gave to the channels their present form and relation. The form of relief in fiords is that to be expected where ice streams have worked; and water is unable to produce such topography.

It has long been supposed that the only reason a fiord channel contains sea-water is because of submergence of valleys carved in the land. Since ice can erode extensively below sea-level, we need postulate no depression to explain the present land and water relations in fiord regions. In fact, fiords cease to be evidence of submergence if they can be formed in some other way. Aside from the apparent drowning, the proof of submergence is very insufficient in fiord regions. Elevated beach-lines and sands are often found several hundred feet or less above the present shore-line, probably indicating a recent lower stand of the land. An elevation is more expectable since the retreat of the ice than a depression, because the quantity of ice, which all believe existed in these regions, would have a tendency to depress the land. Its melting and removal would have permitted the land to rise again. Owing to the great thickness of the ice, sinking, unless very great, would not remove the power of the ice streams to erode the channels. Beach-lines, now high above the present shore-line, may furnish evidence of emergence in recent times.

The cause of the failure by some to recognize fiords as results of ice work is twofold—first, we were unwilling to ascribe such enormous results to glacial erosion; second, we failed to comprehend thoroughly the relation of channel to valley in the case of both water and ice streams. Henry Gannett, of the United States Geologic Survey, furnished suggestive notes on this relation in 1898. It is stated by Davis.* After calling attention to the fact that in each case the channel is that part of the valley occupied by the moving stream, and that the water stream moving rapidly occupies but a very small part of its valley, while the ice stream, moving slowly, occupies a large part of its valley, he says: "A river has a channel with a broadly U-shaped cross-section at the bottom of its V-shaped valley, . . . and . . . a glacier has a V-shaped valley above its U-shaped channel." The fiord valley, so called, is in very large part an ice stream channel, but usually it spreads out above into a V-shaped valley. Believing the fiord to lie in a part of an old ice channel which may open out either into an ice valley or an old river valley, high up, where its walls flare more rapidly, the term "fiord channel" has been constantly used in the present article. This channel is not a valley in the sense that it was made by the stream or body of water that now occupies it. And, if made by an ice stream, the part in which the body of ice lay is not a valley, but is the channel of the ice stream.

The valley of an ice stream possesses parts analogous to those of a river valley, and has them similarly disposed. The floor of the ice channel is uneven in a marked degree; this feature has its analogue, though less conspicuously displayed, in the depressions in the bed of a river which contain pools of water when the stream is so near dry that the water is no longer continuous. The floor or bed of a mature ice channel leading to the sea lies below sea-level at its mouth, provided, of course, that there have been no changes of sea-level since the forming of the channel. So the bed of a mature river, under the same conditions, is below sea-level at the mouth. In the case of the ice channel the depth is as great as the ice can erode it before the water floats the ice. The depth of the floor of the river channel at its mouth is a function of the width and discharge of the river. It will always be sufficient to bring the surface of the outflowing stream approximately to sea-level. The relation of channel floors, of uniting streams of ice, as well as that of uniting river beds, was discussed on a previous page and the similarity indicated. Another resemblance between glacier channels and river channels is found in seeking the line of greatest flow. Both ice streams and water streams have the greatest depth line coinciding with the greatest flow line. Where one departs from the median line, the other follows. Therefore, in the bends of fiord channels, the greatest depth is outside of the centre, as in river channels.

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*Glacial Erosion of the Ticino Valley, Appal., 1900, IX, 154.

It remains yet to discuss the relation of the fiord channels to preglacial valleys. Since the land had been elevated previous to the ice invasion—as shown earlier in the discussion of faults—there must have been valleys of some form at the close of preglacial time. But since it is impossible to determine just what the topography was over which the ice first crept, the absolute amount of ice work in the channels is indeterminable. We know there were folding of strata and faulting before the ice appeared, and its work has been superposed on the topography it found. A measure of the minimum ice erosion can be obtained from the present altitude of the hanging valleys. If streams flowing in them prior to the beginning of ice work entered the streams in the master valleys at almost accordant levels—an expectable feature of streams—the master channel has been cut down by the ice the amount of its present depth below the side channel minus the slight discordance belonging to the earlier water channels. To this may be added any cutting known to have occurred in the side valley during its occupancy by ice.

In the light of the foregoing discussion of the theory of glacial erosion* as the cause of fiords, it appears that the results of previous dynamic processes were not causal in the history of the fiord, but have helped, hindered, or directed the ice in its work, and thereby have given many varieties of form to fiords. The channels were not formed by faults, folds, stream-work, and so on, but were formed in spite of these earlier phenomena. The tendency of the ice was to produce the typical fiord, but where it could not it made the nearest approach to the type. The ice, working on old valleys and mountains, was helped in places, sometimes handicapped, and usually directed by the previous topography; and if unable to make the typical fiord, it made fiord-like forms, now known as fiärden, shären, föhrden, and other less marked geographic features. The dynamic processes, once brought forward as causes of fiords, naturally drop into their proper places. The climatic factors, high latitude and heavy precipitation of snow as conducive to glacial phenomena, may be called secondary or more remote causes of fiords.

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* By glacial erosion the author includes all erosion accomplished by the ice, the tools held by the ice, and the streams beneath the ice charged with sediments.